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Abstract. We discuss the main components of schemes for Lorentz laser-assisted stripping (abbreviated Lolas henceforth) proposed for injection into proton driver accumulators: $H^- \rightarrow H^0 + e^-$ Lorentz stripping, $H^0 \rightarrow H^0(n)$ laser excitation, $H^0(n) \rightarrow p^+ + e^-$ Lorentz stripping. We mention results obtained in practice of H^- beam transport and storage and of experiments addressing physics of the H^- ion, of the H^0 atom and of vacuum, which prove the feasibility of each Lolas component. For high enough injection energies, it is feasible to split without losses the H^0 beam sent towards the accumulator into a fraction stripped to p^+s and stored inside the accumulator and a complementary fraction of H^0s delivered to high duty-cycle users. The fraction of stored beam can exceed 50% with one single Fabry-Perot cavity used to enhance the laser power density. Aspects of Lolas integration and optimization are pointed out.

INTRODUCTION

Schemes for laser excitation and (simultaneous or subsequent) Lorentz stripping of H^0 atoms in the injection straight section of the accumulator of a proton driver have been worked out in Japan, Europe and USA [1-5]. The driving motivation is to design an injection without losses. This requirement is of paramount importance in order to enable improvements by factors exceeding 100 above present injection intensities with foil stripping.

All schemes have common basic ingredients, which include:
1) $H^- \rightarrow H^0 + e^-$ Lorentz stripping.
2) H^0 (1S) $\rightarrow H^0$ (n) laser induced resonant transitions from the H^0 ground state to a Stark sublevel of an n≥3 exited H^0 (n) state,
3) H^0 (n) $\rightarrow p^+ + e^-$ Lorentz stripping in the peak field region of the injection wiggler.

Critical points in all the schemes include:
a) angular dispersion of the H^0 beam,
b) tuning the laser frequency to the resonant transition,
c) tuning stability,
d) power density of the light that induces transitions.

Lolas schemes differ because:
1) H^- stripping is contemplated before or inside the injection straight section of the accumulator,
2) H^0 laser excitation is foreseen in a valley or in a peak of the injection wiggler,
3) The high power density necessary to induce H^0 excitations is achieved with pulsed lasers or with a Fabry-Perot cavity coupled to a CW laser [4].

Because of space limitations we restrict to comments on the main components and critical parts of Lolas schemes, for which refs [1-5] give extended sets of references and the essential formulas.

We mention experimental results [6-14] that prove the feasibility of Lolas components or give direct measurements of parameters of interest. These results are extracted from practice of H^- beam transport and storage and from experiments addressing basic and applied physics of the H^- ion and of the H^0 atom, and of the structure of the physical vacuum.

In most Lolas schemes emphasis is put in maximizing the probability of H^0 stripping at injection. A complementary point of view originates from the observation that proton drivers are necessary both for scientific programs which require high power and low duty-cycle beams (neutrino factory and spallation neutron source) and for programs that require high power and high duty-cycle proton beams (ISOL sources and accelerator driven systems for nuclear waste incineration). The new viewpoint is that it is convenient to foresee from the beginning sharing of the H^0 beam injected into the accumulator between low duty-cycle and high duty-cycle users. The H^0 beam can be split continuously and without losses into two fractions (typically 50/50). One fraction contains H^0s that are excited to one Stark sublevel of an n≥3 level of the H^0 atom and are subsequently fully stripped to p^+s and stored into the accumulator. The second fraction contains H^0s that have remained in the ground state, exit as a good quality beam from the accumulator injection straight section, and are utilized for the high duty-cycle programs. Under these circumstances the high duty-cycle programs run with a fraction of the total H^0 beam intensity that varies between 50% and 100%. Higher intensities for the accumulator users can be obtained by increasing the beam power delivered by the H^- injector linac.

1. H^- STRIPPING

It is convenient to Lorentz strip H^- to H^0 outside the injection section of the accumulator because there one can install a stripper magnet with a small aperture, that enables a high field gradient. This is necessary to minimize the H^0 beam angular dispersion generated by the finite length of the segment of H^- trajectory where H^0s originate from H^- stripping (see ref. 6).

Since the motional electric field E seen in the H^- rest frame by a H^- moving through a magnetic field B is $E \approx 3\beta\gamma B$, the higher the H^- beam energy and the magnetic field intensity and gradient, the easier the stripping and the lower the angular dispersion of the resulting H^0 beam. For calculations and measurements of Lorentz stripping of H^-s see refs [6-8] and [1]. Further relevant references are given in ref [4].

2. H^0(1S)$\rightarrow H^0$(n) EXCITATION

The H^0(n) binding energy is $E(n) \approx 13.6\ n^{-2}$ eV. The energy of the photons necessary to induce transitions from the H^0 ground state to n≥3 levels is above 10 eV. The energy of photons emitted by a NeYAG laser working on the first harmonic is $E_1 \approx 1.17$ eV. The enhancement of the photon energy in the H^0 c.m. system for H^0 atoms colliding head on at high energies with a NeYAG laser beam is $\gamma\ (1+\beta) \approx 2\gamma$. Therefore at $\gamma \approx 2$ (LAMPF and SNS energies) transitions to all excited n levels of H^0 require to use a NeYAG working on the 4^{th} harmonic, at $\gamma \approx 3$ (CERN SPL conceptual design) most transitions can be excited with a NeYAG working on the 2nd harmonic, and at $\gamma \approx 8$ (Fermilab 8 GeV Linac Design Study) all transitions could be induced with a NeYAG laser working on the first harmonic

Transitions from the H^0 ground state to $H^0(n)$ have been studied and measured extensively at LAMPF [9-12]. Photo-excitation of Lyman series of atomic hydrogen for $7 < n < 13$ shows the expected $1/n^3$ amplitude dependence, with saturation onset at $n \leq 8$ [9]. Shifts and broadening of n=4 Stark sublevels of H^0 atoms experiencing motional electric field have been measured with 6 meV experimental width [11].

The techniques used to perform the measurements contain all Lolas basic ingredients. The power of the laser was sufficient to saturate transitions to n<9 levels. Since the laser was pulsed, the power was high and not an issue in these measurements. The effects were studied in coincidence with the laser pulse. Frequency tuning was obtained by changing the angle between particle and light beams. In Lolas scenarios the power is instead a central issue, since one needs to act on all the H^0s of the beam. Pulsed lasers offer high power, but all the difficulties linked to synchronization and matching of laser and beam pulses are present.

Use of a CW-laser beam is obviously simpler and comfortable, and if the necessary power could be obtained the laser light could appear as a passive element just as the foil in foil stripping. The author has suggested the adoption of a Fabry-Perot cavity locked to a CW-laser in order to increase dramatically the laser power density and still work with a CW source. The PVLAS collaboration has developed a Fabry-Perot cavity locked to a NeYAG laser working on the first harmonic [13] and recently also on the second harmonic [14]. PVLAS uses this technique in order to observe and measure directly vacuum polarization effects [13]. In the experiment the FP mirrors are 6 meter apart and light goes back and forth through a 1 m long 6 T superconducting dipole magnet positioned between the two mirrors. So far measurements have been made with a NeYAG working on the first harmonic. The FP finesse is in excess of 10^5. The power density is > 1 $KW \cdot cm^{-2}$. Operating conditions are not less difficult than in a Lolas injection region if one considers that the magnet (and the associated cryostat) rotates mechanically around the FP cavity axis! In spite of all that the cavity stays tuned and locked for hours. This demonstrates that a Lolas scheme would be viable from the power and operation point of view with an accumulator working at $\gamma \geq 6$. Further planned developments will lead to applicability at $\gamma \approx 3$ of the PVLAS technology with a NeYAG working at the 2nd harmonic.

Tuning stability and line broadening are dominated by the energy fluctuations and the momentum dispersion of the linac beam. In order that all H^0s of the beam cross resonant conditions there are two approaches. In the first one there is a constant gradient low magnetic field in the region of crossing of the H^0 and laser beams. A H^0 Stark sublevel has a shift (due to the Lorentz electric field experienced by the H^0 in its rest frame) that varies linearly in first approximation along the crossing region. By adapting conveniently the free parameters dB/ds and B(s) one can manage that all H^0s cross the resonance energy and have ≈50% probability to exit the interaction region in a $H^0(n)$ exited level. In the second approach the magnetic field is high enough in the interaction region to broaden the chosen Stark sublevel so to match the Doppler broadening of the laser light due to the momentum dispersion of the H^0 beam. In the first approach the excited level is narrow and, for a given available light power density, the transition probability is high. However the time for the transition to occur is extremely short since the H^0 stays tuned for a small length of the interaction region. In the second approach each H^0 is always within the resonance width, but the transition probability is lower for the same light power density, because of the broad width of the resonance line. The second approach has the advantage that light induces transitions only one way, since the $H^0(n)$ level is immediately Lorentz stripped in the zero magnetic field gradient interaction region.

3. $H^0(n) \rightarrow p^+ + e^-$ STRIPPING

The binding energy of the electron of an excited $H^0(n)$ atom is $E_n \approx 13.6\ n^{-2}$ eV. For $n \geq 4$ the $H^0(n)$ electron is less bound then the extra electron of the H^- ion, and field ionization is expected to be easier. This is nicely demonstrated by experiments at LAMPF [7, 8] where three beams of H^-, $H^0(n \leq 3)$ and $H^0(n=4)$ move with equal speed through a magnet with large dispersion: at a proper setting of the magnet current the H^- beam is deflected but not dispersed, the $H^0(n \leq 3)$ is not deflected, $H^0(n=4)$ atoms are stripped and the emerging p^+ dispersed. At higher current settings also the H^- beam is stripped, but one observers that the $H^0(n=4)$ beam features less dispersion than the H^- beam.

Dispersion of p^+ from $H^0(n)$ stripping helps for painting in Lolas scenarios. In the scenario where $H^0(1S)$ atoms are excited in the valley of the injection wiggler, and $H^0(n)$ stripping occurs in the peak, the dispersion of the injected p^+ beam is controllable by choosing the wiggler peak field value. In the scenario where transitions are induced to a broadened Stark sublevel, the magnetic field must be uniformed and its value is constrained to be the central one of resonance conditions.

4. INTEGRATION

The basic guideline behind a Lolas H^0 sharing oriented scenario is that efforts to increase the average current in the proton accumulator are directed towards increasing the number of cycles of the H^- linac, by adding the necessary RF power, rather than trying to improve the H^0 stripping efficiency. This procedure would be advantageous for all users, both high and low duty-cycle, because the fraction of H^0 stripped to p^+ and captured into the accumulator stays constant (≈50%). All user communities would be motivated to support intensity upgrades of the linac by acquisition and implementation of additional RF equipment and power. Communities joining later on could contribute additional RF equipment, so improving the average intensity and shortening data taking time for all the other users. In the case of the SPL injection H^- linac proposed at CERN it would be technically feasible to move from 4 to 20 MW beam power at the linac output [15].

In view of the fact that the H^- linac could run all the time, while low duty-cycle programs need shutdown periods, it will be convenient for flexibility and reliability to plan from the beginning:
a) splitting of the H^- beam before the stripping magnet used for injection into the H^0 beam line
b) splitting of the H^0 beam emerging from the accumulator injection straight section, and adequate downstream floor space for high duty-cycle users,
c) a bypass of the injection region of the accumulator, to bring the H^- beam at the start of the H^0 beam line downstream of the accumulator injection straight section (this would permit maintenance work on the accumulator without disturbing high duty-cycle operations of H^0 users).

In order to convert to laser stripping an injection section designed for foil stripping, it might be explored the possibility of exciting resonantly H^- s by inducing transitions to the narrow H^- Feshbach resonance [10].

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